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Debris flow density determined by grain composition

Abstract Density is one of the most important parameters of debris flows. Because observing an active debris flow is very difficult, finding a method to estimate debris flow density is urgently needed for disaster mitigation engineering. This paper proposes an effective empirical equation in terms of grain size distribution (GSD) parameters based on observations in Jiangjia Gully, Yunnan Province, China. We found that the GSD follows $P(D) = KD^{-\mu}\exp(-D/Dc)$, with μ and Dc representing the fine and coarse grains, respectively. In particular, μ is associated with some characteristic porosity of soil in the natural state and increases with increased porosity. Dc characterizes the grain size range of the flow and increases with the grain concentration. Studies show that flow density is related to both parameters in power law. Here, we propose an empirical equation for estimating flow density: $\rho = 1.26\mu^{-0.132} + 0.049Dc^{0.443}$, which provides not only an estimation of the density for a flow, but also describes the variation in density with the GSD of material composition; this provides important information related to the design of debris flow engineering structures.

Keywords Debris flow · Grain composition · Grain size distribution · Debris flow density

Abbreviations

D	Grain diameter (mm)
P (>D)	grains larger than D in millimeters
P (<D)	grains smaller than D in millimeters
μ	A power exponent
D_c	Characteristic size
K	Coefficient, used to be called C in previous papers
D_0	Lower limits of the fractal range
D_m	Upper limits of the fractal range
ρ_f	Debris flow fluid density
ρ_w	Pure water density
ρ_s	Solid density
$\rho_D(D)$	Grain density for particle size D
ρ_c	Average density (ρD(D))
ρ_m	Measured density of debris flow
δρ	Difference in density between the calculated and measured values
σ	Porosity
υ_{fines}	Volume fraction of fluid occupied by fine grains
$P_{0.05}$	Percentage of grains <0.05 mm, in decimal form
P_2	Percentage of grains >2 mm, in decimal form

Introduction

Debris flows are formed from mixture of granular materials ranging from clay to boulders, but contain both granular and continuous features. Thus, the study of debris flows focuses on either granular behavior (Bagnold 1956; Takahashi 1978, 1981, 1991) or the macro-viscous behavior (Rodine and Johnson 1976; Johnson and Rodine 1984; Martosudarmo 1994). Regardless of the exact scenario involved, grain composition is the crucial factor influencing the flow properties, e.g., different grain compositions may result in large differences in frictional shear resistance and pore-fluid pressure (Iverson 2003; Chen et al. 2002; Sassa et al. 2003), and a sufficient amount of clay content is required to support the movement of a debris flow (Pierson 1981; Ellen and Fleming 1987). Observations of active debris flows even suggest that flow regimes and variations are well associated with grain compositions (Li et al. 2014, 2015).

Among the various properties of debris, density is one of the most important (Iverson 1997; Jakob 2005). Density is an integrated index of the constitution of debris flow fluids, and also implies the regime and scale in that high mobility and large-scale debris flows almost always feature high densities (Li et al. 2014). In addition, flow density also serves as a basic parameter related to the design of mitigation structures, which when multiplied by the squared velocity, determines the impact pressure of a debris flow on a structure (Du et al. 1987; Hungr and McClung 1987). Flow density is generally used for engineering designs worldwide (Lo 2000; Sun et al. 2005; Du et al. 1987; Wu et al. 1993). Generally speaking, the flow density primarily determines what measures or structures we employ to prevent disasters.

However, active debris flows are very rarely observed, and today, we are still referring to several old reports from the literature for descriptions of active debris flows (Sharp and Nobles 1953; Curry 1966; Pierson 1986). Experiments provide the main approach used to explore the details of debris flows. However, even in experiments, no ideal techniques have been developed to measure the density, and the noisy, dirty, and inconsistent characteristics of debris flows make it impossible to employ various noninvasive techniques such as ultrasound, X-rays, laser sheets, or magnetic resonance imaging even though they are widely used for other solid-fluid mixtures (Lee et al. 1974; Kytömaa and Atkinson 1993; Graham et al. 1993; Lam 2016). Currently, the most widely accepted method used to measure density involves using deposits to trace the flowing sediments. This is principally reasonable because the deposit of a debris flow is to a great extent a "frozen" flow and retains the original configuration and properties of the flow (Curry 1966; Major 1997; Iverson 1997; Coussot and Proust 1996; Scheidl and Rickenmann 2010). Consequently, flow density is usually estimated by empirical equations based on an analysis of materials deposited from debris flows.

Various equations have been proposed to estimate density using grain size distribution (GSD). For example, some researchers have used median-sized grain (d_{50}), while others used grain content of > 2 or < 0.005 mm (Du et al. 1987; IMDE 1990). However, the grain composition of a deposit, even of a fresh deposit immediately after

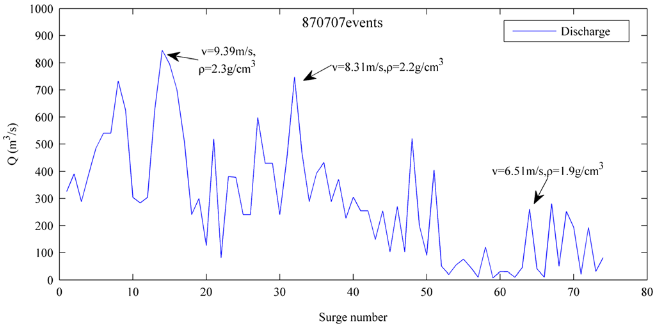


Fig. 1 Fluctuation of flow discharge of a surge group in Jiangjia Gully, 1987

the flow process, is really different from that of the flow body. For instance, d_{50} may vary up to 3–5 mm from the fluid to the deposit. Therefore, these estimations may result in uncertainty of about 0.4 g/cm^3, representing more than 20% of error.

In our previous studies (Li et al. 2015), we found that debris flow density is well related to the GSD parameters in power laws. This study expands the relationship to an empirical equation based on more flow samples from debris flows in Jiangjia Gully, which proves to be more accurate than the previously used equations and is generally applicable for debris flows in different regions.

Data collection

Debris flows in Jiangjia Gully

Jiangjia Gully (JJG) is famous worldwide for its high frequency and variety of debris flows (Liu et al. 2008, 2009; Li et al. 2012); it lies on the right of the Xiaojiang River, a tributary of the upper Changjiang, in northeastern Yunnan, China. The catchment area covers 48.6 km^2 with a 13.9-km long mainstream channel (Fig. 1), an average slope gradient of 16%, and typical local relief of 500 m (Wu et al. 1990). JJG developed along the Xiaojiang fault and experiences intense tectonic movements. Therefore, highly fractured rocks and loose materials are widely distributed over the slopes, which in turn provide numerous sources for landslides and debris flows. Debris flows have occurred frequently during the last few decades, with each event containing tens to hundreds of separated surge waves while each surge varies in density (Liu et al. 2008, 2009; Li et al. 2012). A surge series may exhibit diverse characteristics because, as investigated in the source area of JJG, each surge may come from different tributaries. To describe the process of this phenomenon in the tributary source area, we assume that soil failures or small landslides randomly occur. Therefore, various sizes and amounts of grain components are produced and are washed away by channel flow. Then, the debris flows merge with the mainstream channel downstream. Because of the temporal and spatial randomness of soil failure in the source area, the debris flow surges present a wide diversity of characteristics.

Because materials in any particular debris flow vary greatly since they come from different sources, some feature fine-grained composition while others have coarse-grained composition; the flows appear distinct in grain composition and display various properties. The density of any particular debris flow ranged from 1.5 to 2.2 g/cm^3, the velocity varied between 2 and 12 m/s, and the discharge fluctuated up to three orders of magnitude. Figure 1 shows a series of 75 surges of a typical event in JJG (7 July 1987), indicating the variations of flow density, discharge, and velocity. It also shows that a relatively large-scale and high-velocity surge usually had a high density. All these variations were caused by the variations in material composition, display remarkable relevance to the grain size distribution (Li et al. 2015), and allow us a further exploration the relationship between flow density and grain composition.

Data collection

We observed debris flows in real-time each year during the rainy season. The main variables included flow depth, velocity, duration, discharge, density, sediment delivery, and grain size distribution for different surges (Table 1). Lam (2016) compared the performance of four different slurry density-measurement tools such as mud balance, digital density meter, aerometer, and pycnometer; it was considered that the pycnometer was most likely to be used for the active debris flow density observation, and its accuracy will increase as the measurement volume increases, but the maximum capacity of the pycnometer used in their experiment was 2 l, which was not suitable for measurements of debris flow in Jiangjia Gully. Samples of active debris flows were collected from the moving surges by a suspended cable sampler (Fig. 2), which used a 61-cm tall cylindrical container with an inner diameter of 18 cm and a volume of 0.0155 m^3. Theoretically, it can collect coarse grains as large as 18 cm in diameter, but in fact, most of the largest sample size does not exceed 10 cm. To ensure the comprehensiveness of sampling, when a very small number of debris flows with grains greater than 18 cm occur, a larger sampler is used to sample. Then, the bulk density of each sampled flow was estimated based on the sample. Ignoring the intrinsic fluctuation of a particular surge, the

Table 1 Observed quantities of debris flow surges in Jiangjia Gully

	Flow depth (m)	Velocity (m/s)	Duration (s)	Discharge (m^3/s)	Density (t/m^3)	Volume ratio
1	0.6	5.96	21	71.5	2.27	0.77
2	0.3	3.9	780	5.8	1.83	0.503
3	0.3	2.98	792	7.2	1.75	0.455
4	0.8	6.37	17	51	1.98	0.594
5	1.2	8.08	10	290.9	2.11	0.673
6	0.5	8.84	10	132.6	2.12	0.679

Data source is Dongchuan Debris Flow Observation and Research Station of the Chinese Academy of Sciences; data access is available through official channels. (http://nsl.imde.ac.cn/document/tzgg/show.asp?vid=103)

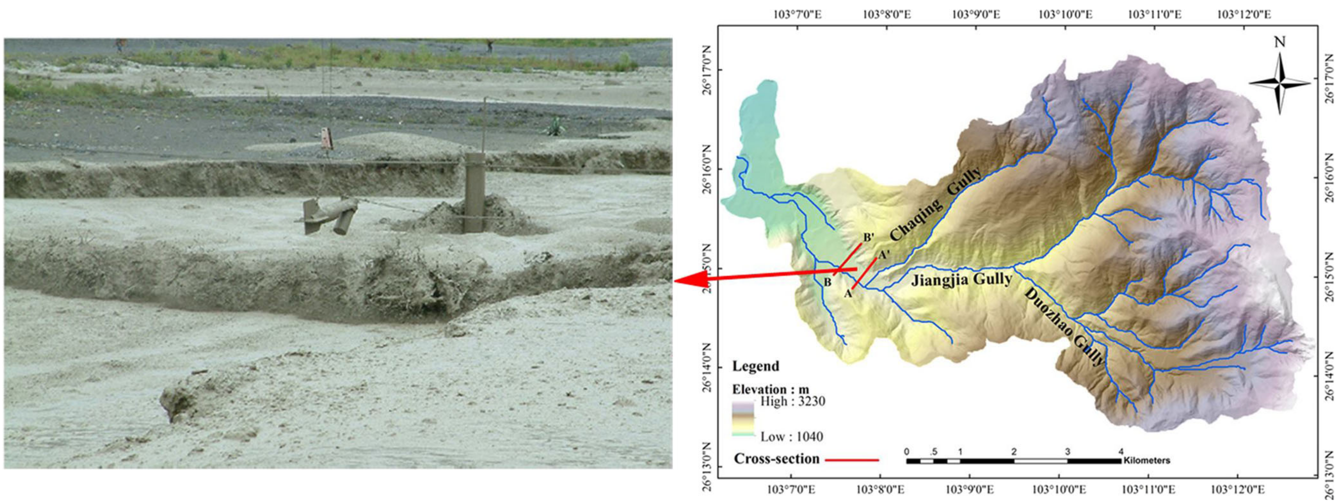


Fig. 2 Location of the study area and sample collection sites. A small inset map shows the study area location within China. A large inset map shows the topography of Jiangjia Gully and the collection sites. A photograph shows one of the sample collection sites

estimated density represents the surge density well. We have hundreds of measured surges, so the data is statistically reasonable.

For each sample, we conduct a granular analysis of the solid materials by the conventional method. The grains ranged between 0.001 and 40–100 mm in diameter; grains larger than 0.25 mm in diameter were sorted by sieving, and smaller grains were sorted by a Mastersizer 2000 laser analyzer (Malvern Instruments Ltd., Malvern, UK). Fig. 3 shows the conventional cumulative curve of the grain size distributions of some samples.

Grain size distribution and density of debris flows

Grain size distribution

The GSD of a debris flow material (from the sources to flows and deposits) satisfies the following expression in Eq. (1) (Li et al. 2013):

$$P(D) = KD^{-\mu}\exp(-D/Dc) \tag{1}$$

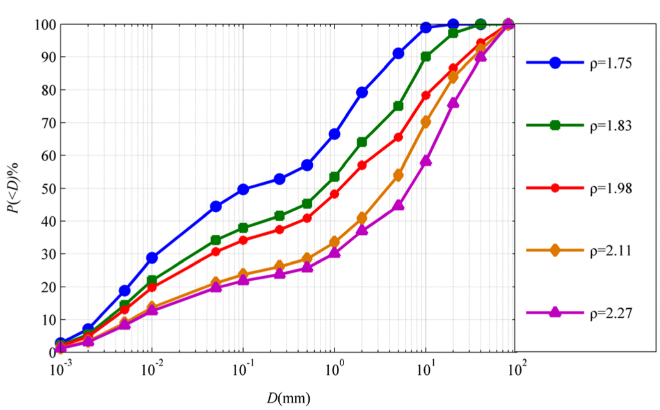


Fig. 3 Gradation curves of different surges in Jiangjia Gully, 2004

where $P(D)$ is the percentage of grains larger than D (mm), and the parameters K, μ, and Dc are directly derived through fitting Eq. (1) to the granular analysis data. Table 2 lists the parameters for different fluids and deposits in different regions, with $R^2 \approx 1$ for most cases that means GSD has a broad universality and can meet the different regions, backgrounds, and properties of the grain size distribution of various debris flows.

When $D << Dc$, Eq. (1) can be simplified to $P(D) \sim D^{-\mu}$; when $D >> 1$ mm, Eq. (1) can be simplified to $P(D) \sim \exp.(-D/Dc)$. This means that μ and Dc represent the fine and coarse components of the grain composition. Moreover, the coefficient K is found to be relevant to μ in a semi-log relationship (Fig. 4).

$$\ln(K) = -a\mu + b \tag{2}$$

Thus, K is not an independent parameter, and the GSD is featured by μ and Dc. The advantage of the GSD relies on the fact that the parameters are directly determined by the full range of grain composition, and the selection of any special parameters is not arbitrary such as occurs with the conventional graphic parameters or some special size such as D_{10} and D_{30}.

Therefore, the GSD can be reduced to the two parameters μ and Dc. Each surge on average is associated with a certain value of μ and Dc. Figure 5 shows the GSD curves of debris flow materials from different regions, showing that μ (or Dc) decreases (or increases) from the upper to the lower portion of the graph. Thus, the parameter pair (μ, Dc) provides an intuitive index of the granular properties of a particular debris flow.

Flow density and grain composition

Debris flow density is usually considered as the density of water plus the density of solid materials and is thus calculated by Eq. (3):

$$\rho_{fluid} = \rho_{solid}\upsilon_{solid} + \rho_w(1-\upsilon_{solid}) \tag{3}$$

Table 2 Grain size distributions for typical debris flows in various regions

Valleys	K	μ	Dc	R^2
Jiangjia Gully flow, Yunnan	52.1	0.092	7.6	0.997
Guanjia, Sichuan	78.9	0.050	10.4	0.958
Shuitang, Sichuan	87.4	0.017	21.6	0.993
Wangjia, Sichuan	71.5	0.049	8.9	0.994
Baishuizhai, Sichuan	86.0	0.030	11.1	0.994
Huangjia, Sichuan	62.6	0.089	10.3	0.996
Mangkang, Tibet	75.5	0.065	28.4	0.993
Batang, Sichuan	62.5	0.099	28.7	0.998
Huanglongtan, Hubei	84.6	0.031	13.4	0.992
Luojiayu, Gansu	92.8	0.022	26.1	0.999

K, coefficient; μ, fine particle content; Dc, coarse particle content

This equation has been widely used in estimating flow density in practice, where the density of solid material is taken as 2.65 in general. In this method, the flow density is simply determined by the water content of the flow. This is, of course, insufficient to reflect the effects of granular materials in a particular debris flow.

However, strictly the solid density depends on the GSD as follows:

$$\rho_{solid} = \int \rho_D(D)p(D)dD \tag{4}$$

where $\rho_D(D)$ is the grain density of size D, and $p(D)$ is the percentage. If we define ρ_c as the average density $(\rho_D(D))$, then Eq. (4) yields as follows:

$$\rho_{solid} = \rho_c \int p(D)dD = \rho_c(1-P(D)) \tag{5}$$

where $P(D)$ is simply the GSD function defined by Eq. (1). Thus, the solid density varies with the upper limit of the grain sizes involved. In particular, when we consider the fine grains of the slurry, which determine the rheology of the flow, the flow density can be expressed as Eq. (6):

$$\rho_{fluid} = \rho_{slurry}\upsilon_{slurry} + \rho_{solid}\left(1-\upsilon_{slurry}\right) \tag{6}$$

In addition, the slurry density, ignoring air content, can be expressed as follows:

$$\rho_{slurry} = \rho_{fines}\upsilon_{fines} + \rho_w\left(1-\upsilon_{fines}\right) \tag{7}$$

where υ_{fines} is the volume fraction of fine grains constituting the slurry, and ρ_{fines} is the density of the fine grain aggregate. Considering $\rho_{\text{dry}} = \rho_{\text{fines}}\upsilon_{\text{fines}}\ (1 - \upsilon_{\text{solid}}) + \rho_{\text{solid}}\upsilon_{\text{solid}}$, we can obtain the expression for υ_{fines} (Iverson 1997):

$$\nu_{fines} = \frac{\left(\rho_{\text{dry}}/\rho_{solid}\right)-\upsilon_{solid}}{1-\upsilon_{solid}} = \frac{\alpha\upsilon_{solid}}{1-\upsilon_{solid}} = \frac{\alpha}{\left(\rho_{solid}/\rho_{\text{dry}}\right)(1+\alpha)-1} \tag{8}$$

where $\alpha = \rho_{\text{solid}}\upsilon_{\text{fines}}(1 - \upsilon_{\text{solid}})/\rho_{\text{solid}}\upsilon_{\text{solid}}$ is the mass of the fine grain ratio in the sediment samples. According to our investigation and analysis in other various regions, the value of υ_{fines} may

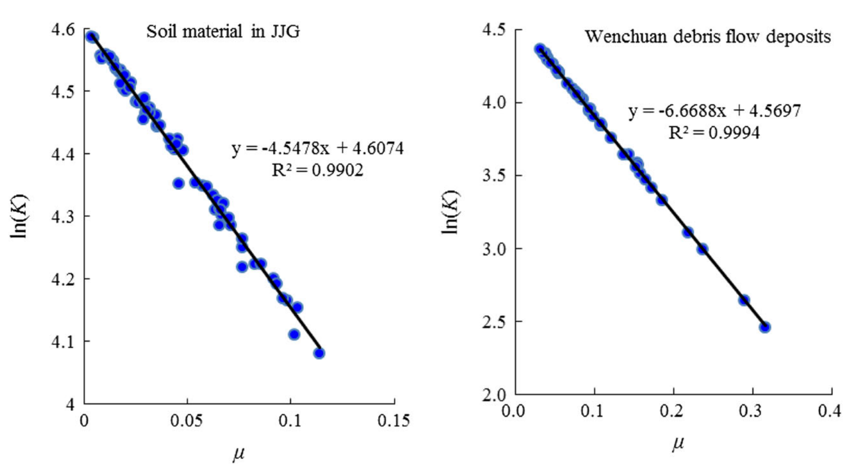


Fig. 4 Relationship between K and μ for different soils. JJG, Jiangjia Gully

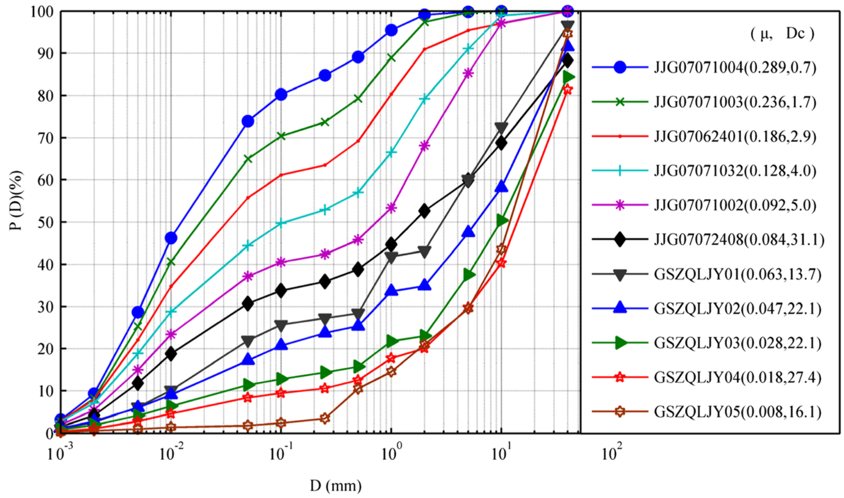


Fig. 5 Variation in (μ, Dc) with gradation curve of debris flows at five sites each in (GSZQLJY) and Jiangjia Gully (JJG). JJG07071004 (0.289, 0.7) means the fourth surge debris flow occurred in JJG in July 10, 2007, and its μ and Dc is 0.289 and 0.7; GSZQLJY01 (0.063, 13.7) means no 01 sample collected from Luojiayu catchments, Zhouqu County, Gansu Province, northwestern China, and its μ and Dc is 0.0.063 and 13.7

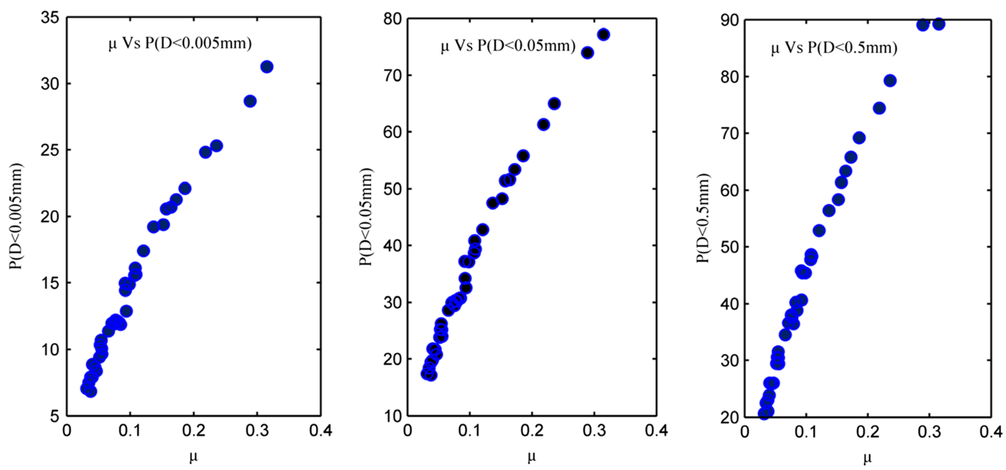


Fig. 6 Relationship between $P(D < D_i)$ and μ in the 2004 Jiangjia Gully debris flow. P ($D < D_i$) is the percentage of grains $< D_i$ (mm)

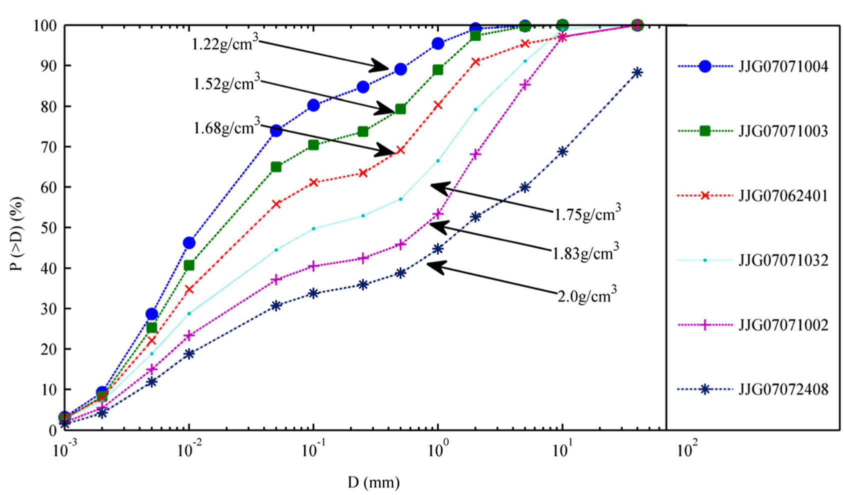
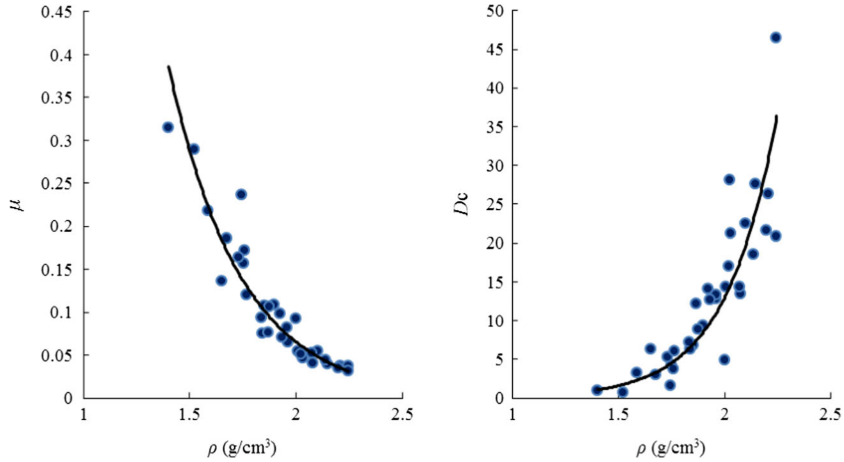


Fig. 7 Density variation with the cumulative curve of grain composition at six sites in Jiangjia Gully (JJG)



(a) The relationship between μ and density ρ (b) The relationship between Dc and density ρ

Fig. 8 Relationship between the grain size distribution parameters and flow density (ρ). (**a**) The relationship between μ and density ρ. (**b**) The relationship between Dc and density ρ

vary from 0.02 to 0.12; thus, the maximum difference in calculated slurry density ρ_{slurry} can reach 0.17 g/cm^3. In fact, the upper limit for the fine grains is by no means a fixed value; instead, it varies remarkably with the bulk constitution of the fluid.

Impact of GSD parameters on flow density

Based on the samples of flow materials, we find that for grains smaller that have a given size D, $P(< D)$ exhibits a nearly linear relationship to the GSD parameter μ, and such a relationship remains until D reaches to ≥ 0.5 mm (Fig. 6). This provides a criterion for determining the upper limit of the "fine" grains; that is, fine grains are those that satisfy the linear relationship to the GSD parameter μ.

In fact, fine grains have appeared to dominate the flow density. Figure 7 shows that cumulative curves for debris flows of different densities present a good coincidence with the parameter μ. The upper curves have relatively a large μ and small D_c, while the flow density increases from upper to lower. This strongly suggests that flow density decreases with μ and increase with D_c.

Relationship of flow density to GSD

A new empirical equation

It is found that the flow density decreases with μ and increases with Dc, both in power law form (Fig. 8).

As a result, an empirical equation was obtained by combining the two power laws, based on data of 120 debris flows in JJG:

$$\rho_f = 1.26\mu^{-0.132} + 0.049{D_c}^{0.443} \qquad (9)$$

This can be explained by the granular structure in terms of the GSD parameters. As discussed above, the GSD in Eq. (1) may be simplified to $P(D) = D^{-\mu}$ for fine grains (i.e., $D << Dc$), and the

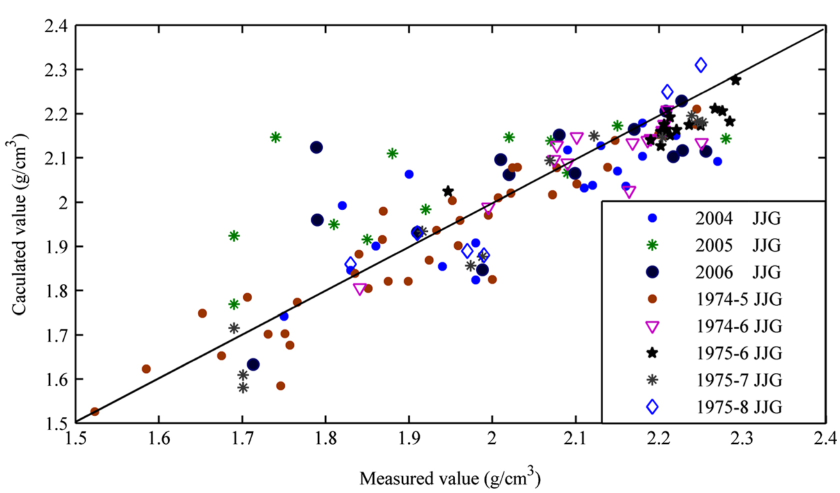


Fig. 9 Relationship between calculated and measured values of debris flow density in Jiangjia Gully

Table 3 Comparison of the measured and calculated debris flow densities in Liuwan Gully (IGC 1982)

Event	C	μ	Dc	ρ_c (g/cm^3)	ρ_m (g/cm^3)	δ_ρ/ρ_m (%)
1963.6.21	61.44	0.0805	18.38	2.12	1.94	8.72
1963.7.1	63.36	0.0752	14.71	2.04	1.93	5.18
1963.7.6	57.28	0.09	16.51	2.11	1.90	9.90
1963.7.24	37.45	0.1769	11.83	2.11	1.73	18.01
1963.8.20	43.03	0.1498	5.15	2.01	1.72	14.42
1963.8.31	72.81	0.0535	19.88	2.02	2.04	− 0.93
1963.8.31–9.1	57.54	0.093	11.31	2.07	1.87	9.78
1963.9.1	49.43	0.1269	17.19	2.21	1.83	17.31
1964.7.1	70.74	0.0575	19.32	2.14	2.02	5.66
1964.7.7	61.97	0.0789	18.31	2.11	1.94	8.08
1964.7.12	64.08	0.0716	19.46	2.11	1.97	6.78

Table 4 Comparison between various equations for debris flow density in various studies

No	Formulas	Authors	Percentage with error below 5%	Percentage with error below 10%
o	Eq. 9	in this paper	73	91
a	$\rho = 1320 \times^{7}-513 \times^{6} + 891 \times^{5}-55 \times^{4}+ 34.6 \times^{3}-67 \times^{2} + 12.5\times + 1.55$	Chen et al. (2010)	57	61
b	$\rho = 1.887 d_{50}^{0.0779}$	Li and Liang (1982)	61	89
c	$\rho = 2P_{0.05}^{0.35}P_2 + 1.5$	Yu (2008)	58	67
d	$\rho = 1.22\exp(-2.283\ \mu) + 0.479Dc^{0.246}$	Li et al. (2015)	63	85

x is the fraction of fine grains < 0.005 mm; d_{50} is the median grain size; $P_{0.05}$ is the percentage of grains <0.05 mm; P_2 is the percentage of grains > 2 mm

parameter μ is associated with porosity (Katz and Thompson 1985; Rieu and Sposito 1991; Hunt 2004; Li et al. 2013):

$$\sigma = 1-(D_o/D_m)^{\mu} \tag{10}$$

where D_o and D_m are the lower and upper limits of the scaling law $P(D) = D^{-\mu}$. Nevertheless, a small μ means the debris flow has a small measured porosity, and hence, an increase of excessive pore pressure occurs during a debris flow, which eventually results in an increase in flow mobility and transportation capacity (Pierson 1981; Iverson et al. 2000). As a result, the flow may transport increasingly greater amounts of coarse grains and raise the sediment concentration, which is positively characterized by Dc. Therefore, the small μ is associated with a large Dc, and both contribute to an increase in flow density.

Appendix 1 lists the GSD parameters and the resulting flow density for some surges in JJG, showing a good agreement with the field observations (Fig. 9). The relative error $\delta\rho/\rho_m = (\rho_c - \rho_m)/\rho_m$ is as small as ± 5% for about 80% of the surges, and ± 10% for about 98% of the surges. Large errors occur mainly in flows of low densities (below 1.8 or so), where the granular effects are obviously smaller.

Verification and comparison

The proposed Eq. 9 is based on the data from JJG; now, we apply it to other cases for verification. Since active debris flows are rarely

Table 5 Results of analysis of debris flow particle composition (Chen et al. 2010)

Grain size (mm)	> 100	100 ~ 80	80 ~ 60	60 ~ 30	30 ~ 20	20 ~ 10	10 ~ 5
Fraction (%)	3.65	0.67	22.49	4.95	4.55	5.79	4.9

Grain size (mm)	5 ~ 2	2 ~ 0.1	0.1 ~ 0.05	0.05 ~ 0.01	0.01 ~ 0.005	< 0.005
Fraction (%)	7.9	30.85	4.12	5.29	1.48	0.67

Table 6 Comparison of equations for a special debris flow

Method	Observed value	Equation (9)	Chen et al's. (2010) method	Li and Liang's (1982) method	Li et al's. (2015) method	Yu's (2008) method
ρ (g/cm^3)	1.97	2.06	1.63	1.99	2.34	1.94

seen and sampled in the field, adequate real-time observational data are normally lacking. Fortunately, we found a group of debris flows from Liuwan Gully in Gansu Province, in western China (IGC 1982). Table 3 lists the involved GSD parameters and the calculated flow density in comparison with the measured values, showing that most cases the estimates had errors of > 10%. This confirms the applicability of the equation to the estimation of debris flow density.

Moreover, we can make comparison with other equations for debris flow density. Table 4 lists five equations (including the present Eq. 9 of ours) and compares their resulting calculations for the data from JJG used in the present study. This shows that the error of our Eq. 9 is remarkably smaller than the others. Note that all the equations are mainly based on the JJG data, so the comparison is statistically meaningful.

More convincingly, we apply these equations to a special debris flow event in another gully, the Yang Fang Gully, southwest Sichuan, hundreds of miles from JJG and Liuwan Gully. Details of the event can be found in Chen et al. (2010), and the measured flow density was 1.97 g/cm^3. Table 5 lists the grain composition and the GSD parameters μ and Dc were 0.0826 and 63.21 mm, respectively. These values are conspicuously different from most cases in JJG (Appendix 1), suggesting the material sources of this gully are distinctly different from those of JJG. Table 6 lists the calculated results using the above five equations, showing that the proposed Eq. 9 is applicable.

Discussion

This study proposed a new equation to describe the grain size distribution of debris flows, where the parameters μ and Dc can represent the content of coarse and fine grains, respectively; this means that debris flow from various regions can be characterized and distinguished by these two parameters, so this equation can better explain the effect of grain composition on the density of debris flow and there is no need to consider regional differences in the study of characteristics of debris flows. So, the proposed equation can better explain the effects of grain composition on the density of a debris flow. Because parameters μ and Dc are sensitive to variations in grain composition, they can be used to depict the evolution of a debris flow. A change in the frequency of fine or coarse grains in a debris flow may lead to a change of μ and Dc and finally, can lead to a fluctuation of density. Therefore, we can combine the characteristics of the flow basin and use the numerical simulation of random grain mixture to predict the dynamic variation of debris flow density. We hope our methods that are used to calculate debris flow density could facilitate the assessment debris-resistant barriers.

Conclusion

Debris flow materials satisfy a universal grain size distribution of $P(D) = KD^{-\mu}\exp(-D/Dc)$, and the grain composition of a debris flow as a whole can be well represented by μ and Dc, respectively, representing the fine and coarse grain content.

The parameters and the density had a good correlation: $\rho = 1.26\,\mu^{-0.132} + 0.049Dc^{0.443}$. This equation works well for debris flows in various regions. When compared with other empirical equations, our proposed equation has the advantage that the parameters used in the equation are naturally determined by the grain composition, without artificial selection of any special grain sizes needed to solve the equation. More importantly, because the GSD remains the same during the flow evolution, the equation can be used to trace the variation in debris flow density with the changes in grain composition in a developing debris flow.

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